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A comparison of 10^3–10^5 year uplift rates on the South Alkyonides Fault, central Greece: Holocene climate stability and the formation of coastal notches

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[1] Measurements of Holocene coastal notch sequences exposed in the footwall of the active South Alkyonides normal fault, Greece, reveal 3 Holocene paleoshorelines near the lateral fault tip, rising in elevation eastward toward the center of the fault, where a 4th paleoshoreline appears. The implied eastward increase in Holocene uplift rate mirrors that for an uplifted Quaternary marine terrace (0.29 mm/yr–0.55 mm/yr from west to east). Assuming these uplift rates were constant through the Holocene, notch elevations predict ages of 650, 1900, 3700 and 6500 years B.P., comparable with published ^{14}C ages on notch fauna, and well correlated with periods of relatively stable Holocene climate. We propose that the notch sequences formed when post-glacial sea level rise became outpaced by the coastal uplift rate, whilst individual notches formed when stable climate facilitated sustained erosion. The parity of the Holocene and Quaternary uplift rates suggests that notch sequences could be used to characterize long-term patterns of uplift, slip-rate and seismic hazards on active normal faults, if 6500 years is long enough to fully characterize temporal variation in the seismic cycle.

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1. Introduction

[2] Uplifted Holocene coastal notches are features of rocky coastlines that form at mean sea level by processes of abrasion, dissolution and biological activity [*Kershaw and Guo*, 2001]. Such paleoshorelines are measurable indicators of shoreline uplift, and can provide useful constraints on uplift rates in geologically active areas at sea level, such as central Greece. However, there is currently no consensus on exactly how notches form. For example, it is commonly assumed that the rate of eustatic sea level rise must match the rate of tectonic uplift for notches to form. This implies that the rate of relative sea level rise must slow relative to the tectonic uplift rate for notches to emerge above sea level.

[3] Also, it is unclear whether Holocene uplift rates reflect the long-term, multi-seismic-cycle fault slip-rate, or record transient periods of rapid seismic activity. For example, ^{36}Cl exposure dating of fault planes in the Mediterranean has shown that Holocene slip-rates on a single fault varied from c. 1.7 mm/yr for the period 12–5 ka, to zero from 5 ka to present (Magnola Fault, Italy) [*Palumbo et al.*, 2004]. This pattern of behavior appears to be typical of active normal faults in the Mediterranean, such as the Kaparelli and Sparta normal faults in Greece which both show evidence for periods of heightened activity lasting several thousand years followed by similar time periods of relatively low slip-rate or quiescence [*Benedetti et al.*, 2003; *Benedetti et al.*, 2002]. Do raised notch sequences also record such deformation rate variations? Answering this question is crucial if notches are to be used as effective tools to assess the long-term rates of active deformation and seismic hazards.

[4] The Perachora Peninsula (Figures 1a and 1b) is an area of active faulting and coastal uplift that has been the focus of numerous uplifted notch studies [*Pirazzoli et al.*, 1996; *Pirazzoli et al.*, 1994; *Stiros and Pirazzoli*, 1998; *Kershaw and Guo*, 2001]. Notches are well preserved here due to a small tidal range of c.10–20 cm. The southern coastline of the peninsula lies in the immediate footwall of the active E-W striking South Alkyonides normal fault (SAF) that ruptured with meter-scale surface offsets in the 1981 Gulf of Corinth Earthquake Sequence [*Jackson et al.*, 1982] (Figures 1b and 1f). This sequence of earthquakes produced both coastal uplift and coastal subsidence in the surrounding region [*Vita-Finzi and King*, 1985; *Hubert et al.*, 1996]. Paleoseismological trenching has shown that surface ruptures also occurred at 1295–1680 A.D. and 670–1015 A.D. [*Collier et al.*, 1998], but it is unknown if these earthquakes produced any coastal uplift.

[5] Here we present notch elevation measurements along a c. 5 km stretch of coastline eastward from the western lateral tip of the fault that ruptured in 1981 and a few kilometers into the footwall of the surface ruptures. We compare the Holocene uplift with Quaternary uplift rates (0.29–0.55 mm/yr west-east) derived from an elevated marine terrace whose formation has been constrained by ^{234}U–^{230}Th coral dating to correspond to a 125 ka interglacial sea level highstand [*Leeder et al.*, 2003] and has been mapped by us at 1:5000 scale. We show that uplift rates from this Quaternary marine terrace and the Holocene notches are similar because the implied notch ages are consistent with ^{14}C ages of notches along the Perachora Peninsula [*Pirazzoli et al.*, 1994]. Tilting of both Quaternary and Holocene paleoshorelines toward the fault tip demonstrates that uplift is related to displacement gradients on the fault rather than regional processes. Individual notches are

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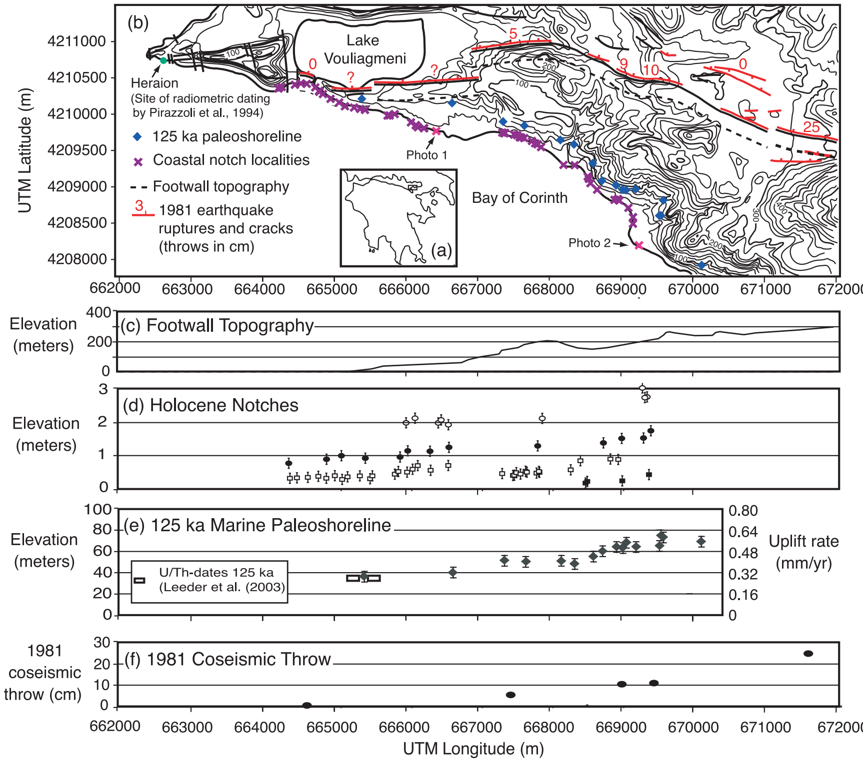

Figure 1. (a) Map of Greece. (b) Map of the Perachora Peninsula showing locations of uplifted coastal notches, raised 125 ka paleoshoreline, 1981 earthquake ruptures, and SAF footwall topography. Photos 1 and 2 refer to notch photographs in Figure S1 of the auxiliary material. (c) Footwall topographic profile. (d) Elevations of raised Holocene notches showing a 4th notch appearing at the base of the sequence to the east. (e) Measured elevations and corresponding uplift rates of the 125 ka paleoshoreline. (f) Coseismic throw associated with the 1981 earthquake sequence.

too large and too few to be explained by uplift due to individual surface rupturing earthquakes [see also *Stewart and Vita-Finzi*, 1996]. Instead, we show for the first time that notches formed during periods of relatively stable Holocene climate [*Mayewski et al.*, 2004], which allowed sustained biological, chemical and physical erosion. The parity between long-term, multi-seismic-cycle uplift (10^5 years), and uplift over shorter time periods (10^3 years), suggests relative stability of the slip-rate for the duration of several seismic cycles rather than transient periods of rapid seismic activity.

2. Measurements and Modeling

[6] All notch sequences along the southern coast were located using a hand-held GPS and 1:5000-scale maps, whilst elevations of individual notches and the geometry of notch sequences were recorded photographically and with steel rules (see photographs in auxiliary material).[1] Notches are only preserved where limestone or lithified Quaternary conglomerates crop out on the coast, so they are discontinuous along strike (Figure 1b). Where preserved they are characterized by decimeter-scale concave abrasion surfaces coated by marine fauna such as barnacles, and bored by lithophagid bivalves [*Pirazzoli et al.*, 1994]. The paleoshoreline location for each notch was recorded as the midpoint on the concave notch profile, since this averages the paleoshoreline elevation if uplift was ongoing during notch formation. This method assumes that the paleoshoreline is likely to lie above the lower part of the concave profile (formed predominantly by submarine wave action, marine dissolution and biological abrasion/boring) and below the higher part of the concave profile (formed predominantly by subaerial wave action, dissolution via water splash, and colonization by intertidal/splash-zone organisms). The error associated with this method is on the order of ±10 cm (see auxiliary material for a more detailed explanation). Instead of assuming the lowest notch is the same age along strike, notch interpretations were made from lowest to highest working from west to east. A younger notch appears in the east using this technique (Figure 1d).

[7] The elevation of the 125 ka paleoshoreline is constrained by $^{234}U-^{230}Th$ dating of *Cladocora* corals along the southern coast of the Perachora Peninsula [*Leeder et al.*, 2003]. We mapped this paleoshoreline to the east away from the dated site onto 1:5000 topographic maps with contours every 4 meters (Figures 1b and 1e). The paleoshoreline is marked by a prominent break of slope along most of its length, where a marine wave-cut platform abuts a paleo-sea-cliff/rocky shoreline. The break of slope is marked in many places by lithophagid borings on the paleo- sea-cliff/rocky shoreline, and the wave-cut platform is in places covered with shoreface bioclastic sands with coral, bivalve and echinoderm fragments. At two locations a sequence of

[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL030673.

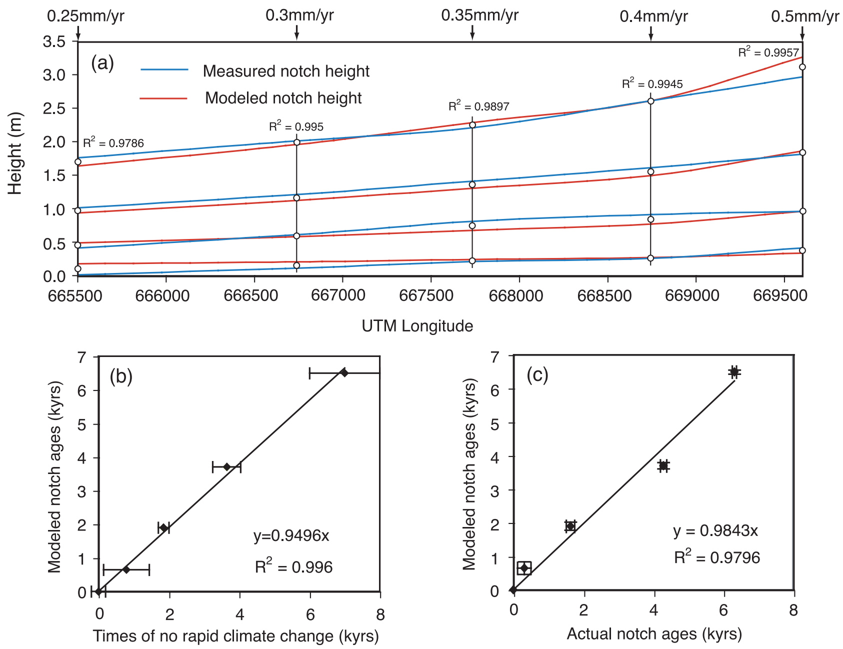

Figure 2. (a) A comparative plot of measured notch profiles and notch profiles derived from iterative numerical modeling assuming a constant Quaternary uplift rate of 0.29–0.55 mm/yr. R^2 values indicate fit between measured and modeled notch heights at different uplift rates (an R^2 of 1.00 indicates perfect correlation, while an R^2 of 0.00 indicates no correlation). (b) Modeled notch ages plotted as a function of times of no RCC after *Mayewski et al.* [2004]. (c) Modeled notch ages plotted as a function of actual notch ages from ^{14}C dating by *Pirazzoli et al.* [1994].

coastal notches, comparable to those observed at modern-day sea level were also preserved. Although clear on the topographic maps, we also checked the position and elevation of each paleoshoreline using hand-held GPS receivers with built-in barometric altimeters. We set two altimeters to zero meters elevation on the modern beach and then climbed to the paleoshoreline and measured the change in elevation, finally returning to modern sea level to check that the altimeters returned to zero. Paleoshoreline elevations were measured within a few tens of minutes of the elevation calibration to modern sea level, negating any errors due to changes in atmospheric pressure; the results from the two altimeters agreed to <±1 meter, and confirmed the elevations derived from the 1:5000 topographic map. We are confident that our reported elevations for the 125 ka paleoshoreline are accurate to less than ±4 meters, which is sufficient for our purposes.

[8] Once field measurements were complete, we carried out numerical modeling to assess the ages of the notches. Assuming that the Holocene uplift rate matched the 0.29–0.55 mm/yr uplift rate derived from ^{234}U–^{230}Th dating of corals on the uplifted 125 ka marine terrace [*Leeder et al.*, 2003], the height of each notch becomes a proxy for its age.

[9] The tilted geometry of the notches along the Perachora coastline mirrors tilting of the 125 ka marine terrace and reflects differential uplift of the fault and a change in uplift rate along strike from 0.29 mm/yr in the west to 0.55 mm/yr in the east (Figures 1d, 1e, and, 1f). Uplift rates were thus extracted from five points along the uplift profile, taking the point of highest notch elevations as having the maximum 0.55 mm/yr uplift rate. Best-fit ages for each notch were then derived using an iterative process of matching the measured notch profiles with the resulting modeled profiles evidenced by high R^2 values (Figure 2a).

3. Results

[10] The Perachora Peninsula preserves a discontinuous set of four Holocene notches along strike of the E-W trending fault that ruptured in 1981. The notches are tilted along strike, with the fourth and lowest notch developed only in the east where uplift rates are highest. Numerical modeling of measured notch elevations assuming a differential east-west Quaternary uplift rate of 0.29–0.55 mm/yr suggests that the notches formed at 650, 1900, 3700 and 6500 years B.P. These ages are comparable with radiometric ages of 310 ± 190, 1635 ± 125, 4300 ± 90, 6330 ± 60 years B.P. from *Notirus irus* shells collected from notches exposed at Heraion (Figure 1a) and Mylokopi on the northern Perachora coast [*Pirazzoli et al.*, 1994].

[11] A recent study of Holocene climate variability through analysis of globally distributed high-resolution climate proxy records [*Mayewski et al.*, 2004], suggests that over the past 6500 years, the Earth's climate has oscillated on a fairly regular basis between periods of stable climate and times of significant rapid climate change. When modeled notch ages are compared with this Holocene climate record, it appears that they fall within periods of climate stability or no rapid climate change (Figure 3). Thus our preferred model for notch formation is that steady climate provides a sustained period of biological, physical and chemical erosion for the creation of a distinct concave notch. The presence of coastal notch sequences at two sites along the raised 125 ka paleoshoreline suggests that the same controls on notch development have occurred during

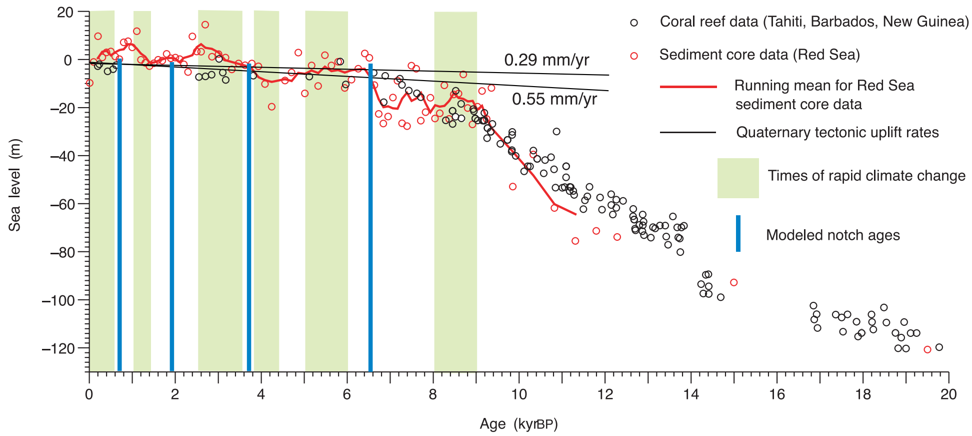

Figure 3. A combined plot of Holocene sea level fluctuations from global coral reef data [*Bard et al.*, 1990; *Fairbanks*, 1990; *Edwards et al.*, 1993; *Bard et al.*, 1996] and Red Sea sediment core data [*Siddall et al.*, 2003], Quaternary uplift rates [*Leeder et al.*, 2003], times of no rapid climate change (RCC) from *Mayewski et al.* [2004], and modeled notch ages.

previous interglacials and may therefore reflect the standard situation for periods of higher global temperature. We discount the idea that notches form through variations in wave activity caused by storms or changes in wave fetch, since variations in storm activity are unlikely to last long enough to carve significant notches and the relative positions of the landmasses around the Gulf of Corinth have remained virtually unchanged for the last 6 kyrs. We also discount any direct correlation between the notches and individual seismic events since paleoseismological studies on both the SAF [*Collier et al.*, 1998; *Pantosti et al.*, 1996] and the neighboring Eliki fault [*Stewart and Vita-Finzi*, 1996] indicate that earthquakes in the vicinity have been too small ($\leq$1.2 m vertical displacement) and too numerous (330–740 yr recurrence intervals imply tens of earthquakes since 6 ka) to explain the carving and uplift of four distinct notches. Even the 1981 M_s 6.7 earthquake produced <10 cm of uplift [*Hubert et al.*, 1996], too little to have raised a notch clear of the water level.

4. Discussion

[12] Our preferred interpretation is that individual notches are formed during periods of no rapid climate change (no RCC) when the rate of sea level rise is outpaced by the rate of tectonic uplift. Until 6 ka, the rate of sea level rise was very high (~10 mm/yr) [*Siddall et al.*, 2003] (Figure 3) and significantly outpaced tectonic uplift (0.29–0.55 mm/yr). However, it slowed rapidly around 6 ka to values similar to or less than the rate of tectonic uplift, corresponding well with the 6500 yr B.P. age of the oldest Holocene notch (Figure 3). We suggest that at this time, the rate of tectonic uplift overtook the rate of sea level rise. During periods of climatic stability (no RCC), bioproductivity of rock boring and grazing biota such as cyanobacteria, limpets, chitons, clinoid boring sponges, sea-urchins and lithophagid bivalves [*Laborel and Laborel-Deguen*, 1994] will reach a maximum, allowing rapid formation of a concave notch (Figure 4a; t_1). Then, as climate again becomes unstable (RCC), notch formation terminates, but because coastal uplift outpaces sea level rise, the notch is lifted out of the water and preserved as a raised Holocene shoreline (Figure 4a; t_2). Finally, climate settles once more (no RCC), allowing a new notch to form at sea level (Figure 4a; t_3).

[13] Our findings suggest that the rate of Holocene slip along the SAF, as evidenced by uplift rates, closely matches the longer-term Quaternary slip-rate as evidenced by elevations of the 125 ka paleoshoreline. However, note that there is no reason why the rate measured in part of the Holocene (6 ka to present) should equal the Quaternary rate, because we know that other active normal faults in the Mediterranean experience quiescent or high-activity periods that last this long [e.g., *Palumbo et al.*, 2004]. For example, three hypothetical slip-rate history curves for the SAF are illustrated in Figure 4b. In model A, constant earthquake slip magnitudes and recurrence intervals produce a Holocene slip-rate that matches the long-term, multi-seismic-cycle slip-rate. In model B, slip-rate matches the long-term rate, but diverges significantly from it on the shorter timescale, with zero slip during the Holocene. In model C, the Holocene slip rate happens to match the long-term slip rate, but is more variable over longer time periods. Therefore, while the apparent parity of the Holocene and Quaternary uplift rates measured in this study suggests that notch sequences can be used to characterize long-term patterns of uplift, slip-rate and seismic hazards on active normal faults, this may be coincidental; Model A or Model C in Figure 4b could apply. Further studies of both Holocene and Quaternary slip are needed to fully constrain the natural variability in the seismic cycle.

5. Conclusions

[14] Holocene coastal notches along the southern coastline of the Perachora Peninsula, central Greece, were formed during periods of stable climate when post-glacial sea level rise was outpaced by coastal uplift rate. Holocene uplift rates derived from these notches closely match calculated Quaternary uplift rates from an adjacent marine terrace, suggesting that uplift rates on the SAF have been consistent over the 10^3–10^5 year timescale. However, this may be a coincidence as ^{36}Cl exposure ages of other faults in the region show that earthquakes cluster in time, producing slip-rate transients. Further studies should concentrate

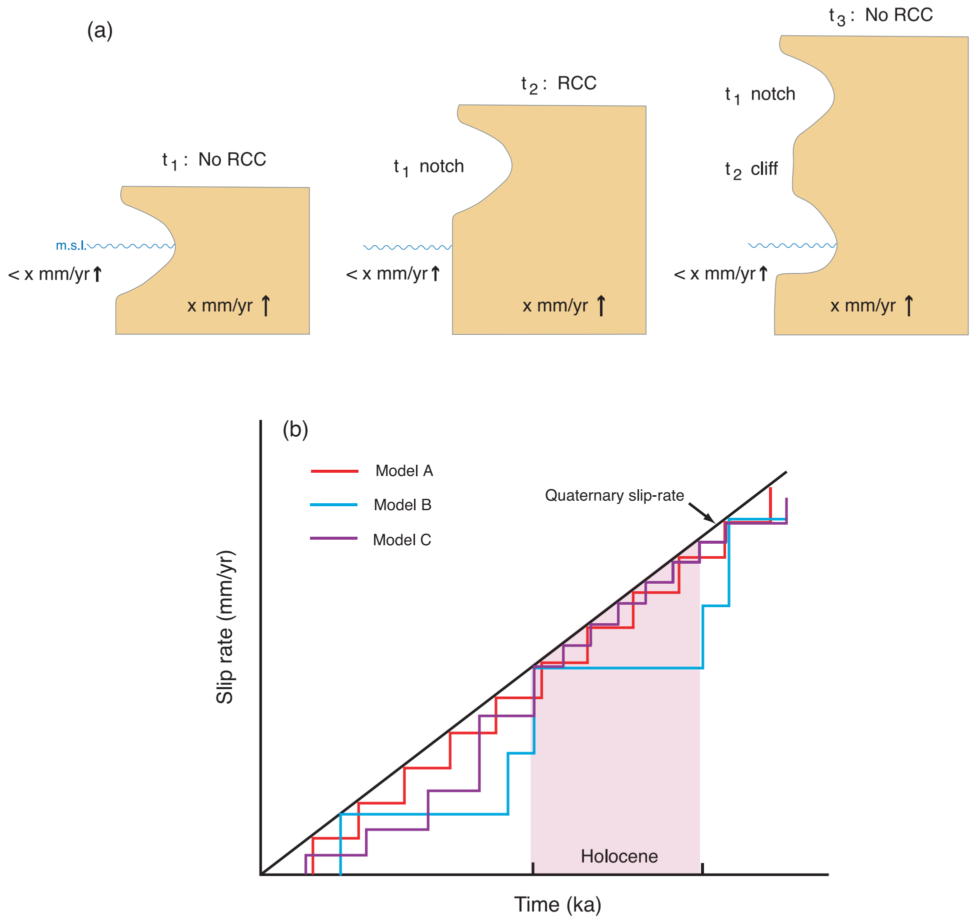

Figure 4. (a) A schematic illustration of notch formation related to climate stability. The coastline uplifts at a rate of x mm/yr while mean sea level rises but does not keep pace with coastal uplift (< x mm/yr). At time 1 (t_1), there is no RCC, providing stable conditions for organisms to carve a notch in the sea cliff. By time 2 (t_2) the notch formed at t_1 has been uplifted out of the water and climate is now unstable (RCC). This means that organisms are unable to carve a new notch, so the steep sea-cliff remains. At time 3 (t_3), both the t_1 notch and t_2 sea-cliff are uplifted out of the water and a new period of climatic stability allow organisms to create a new notch at sea level. (b) Three hypothetical slip-rate models for the South Alkyonides Fault.

on constraining the natural variability in the seismic cycle over time periods longer than the Holocene.

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